US012044769B2

(12) **United States Patent**
Yehezkel et al.

(10) **Patent No.: US 12,044,769 B2**
(45) **Date of Patent: Jul. 23, 2024**

(54) **ELECTRONIC DEVICES WITH LOW SIGNAL-TO-NOISE RATIO RANGE MEASUREMENT CAPABILITIES**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 356 days.

(21) Appl. No.: **17/364,590**

(22) Filed: **Jun. 30, 2021**

(65) **Prior Publication Data**

US 2023/0003867 A1 Jan. 5, 2023

(51) **Int. Cl.**
G01S 13/34 (2006.01)
G01S 7/35 (2006.01)
G01S 13/58 (2006.01)

(52) **U.S. Cl.**
CPC ***G01S 13/34*** (2013.01); ***G01S 7/354*** (2013.01); ***G01S 13/584*** (2013.01)

(58) **Field of Classification Search**
USPC 342/91
See application file for complete search history.

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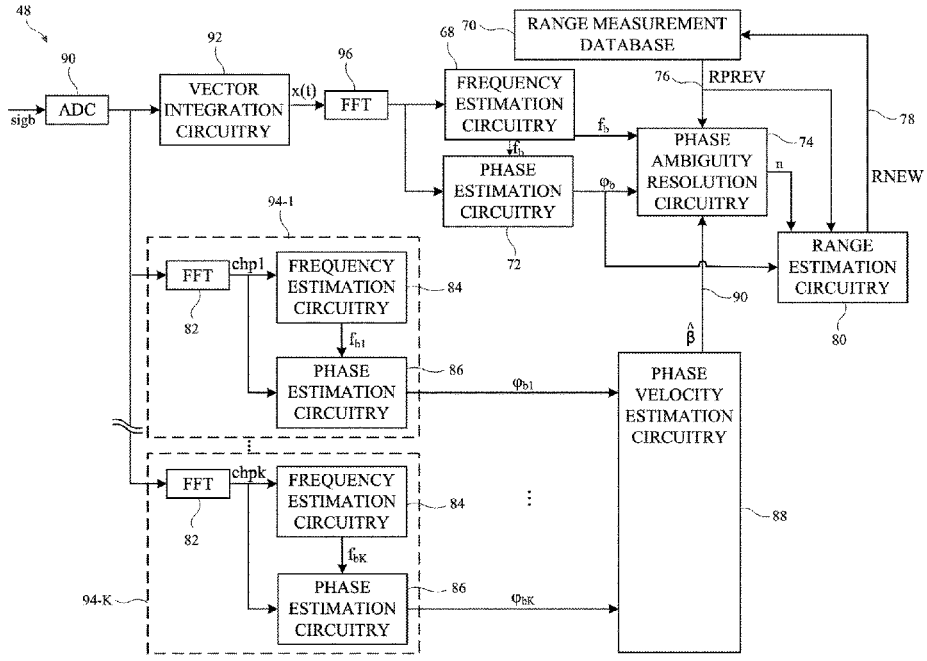
(57) **ABSTRACT**

An electronic device may include wireless circuitry with sensing circuitry that transmits radio-frequency sensing signals and receives reflected radio-frequency sensing signals. A mixer may generate a series of beat signals based on the sensing signals and the reflected sensing signals. The sensing circuitry may generate a beat phase based on an average of the series of beat signals, a set of phase values based on the series of beat signals, and a phase velocity based on the set of phase values. The sensing circuitry may resolve a phase ambiguity in the beat phase based on the phase velocity to identify a range between the electronic device and an external object. This way may allow the sensing circuitry to generate accurate ranges even in a low signal-to-noise ratio regime, such as when the external object is moving relative to the electronic device.

20 Claims, 9 Drawing Sheets



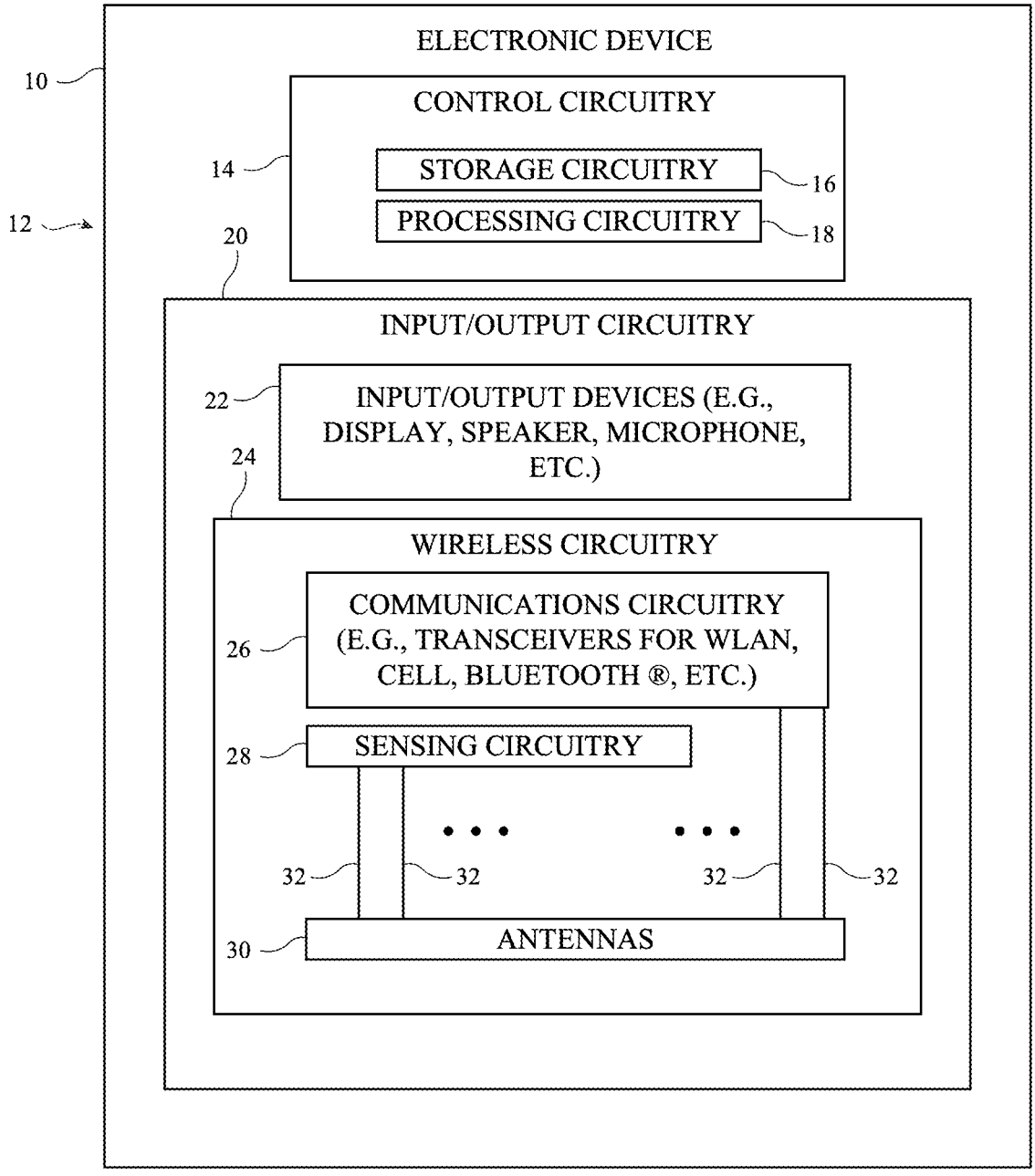

ELECTRONIC DEVICE
10
CONTROL CIRCUITRY
14
STORAGE CIRCUITRY
16
12
PROCESSING CIRCUITRY
18
20
INPUT/OUTPUT CIRCUITRY
22
INPUT/OUTPUT DEVICES (E.G., DISPLAY, SPEAKER, MICROPHONE, ETC.)
24
WIRELESS CIRCUITRY
COMMUNICATIONS CIRCUITRY (E.G., TRANSCEIVERS FOR WLAN, CELL, BLUETOOTH ®, ETC.)
26
SENSING CIRCUITRY
28
32
32
32
32
ANTENNAS
30

FIG. 1

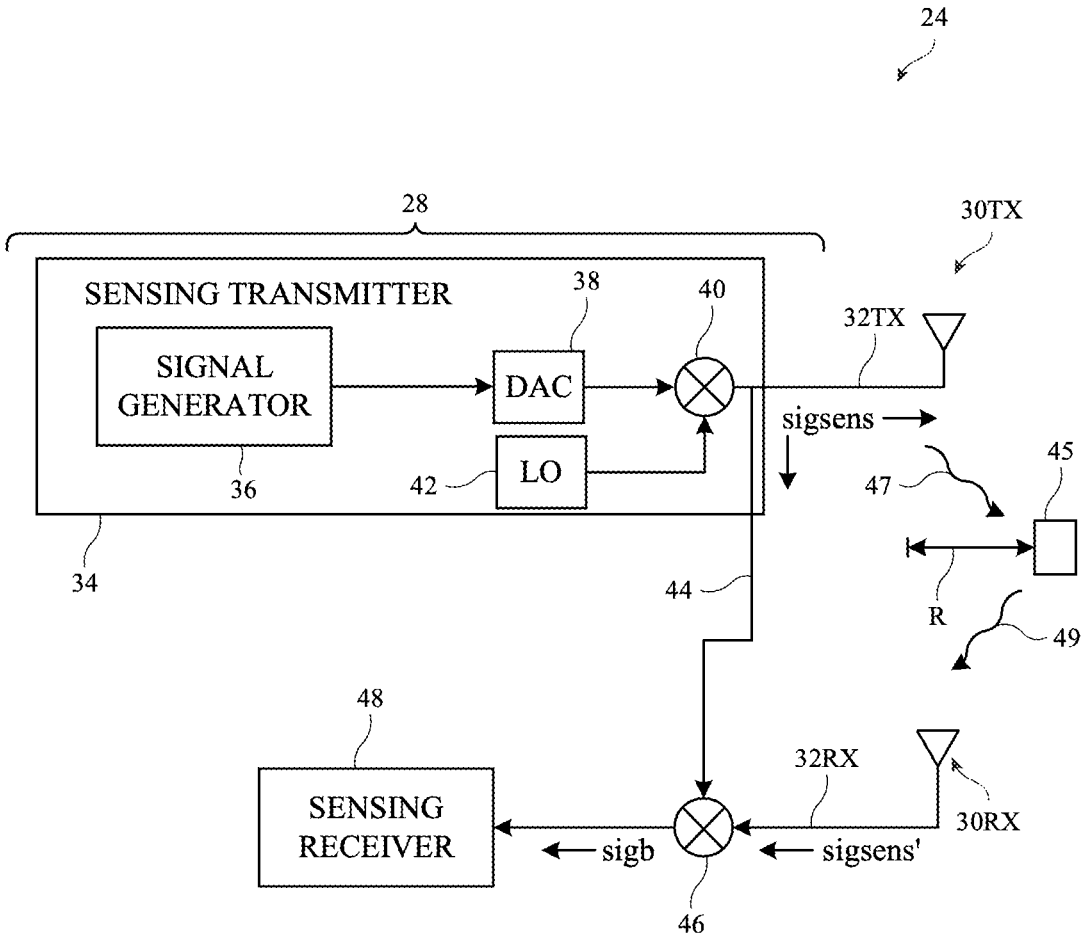

24
28
30TX
SENSING TRANSMITTER
38
40
32TX
SIGNAL GENERATOR
DAC
sigsens
45
47
LO
42
36
34
44
R
49
48
32RX
SENSING RECEIVER
30RX
sigb
sigsens'
46

FIG. 2

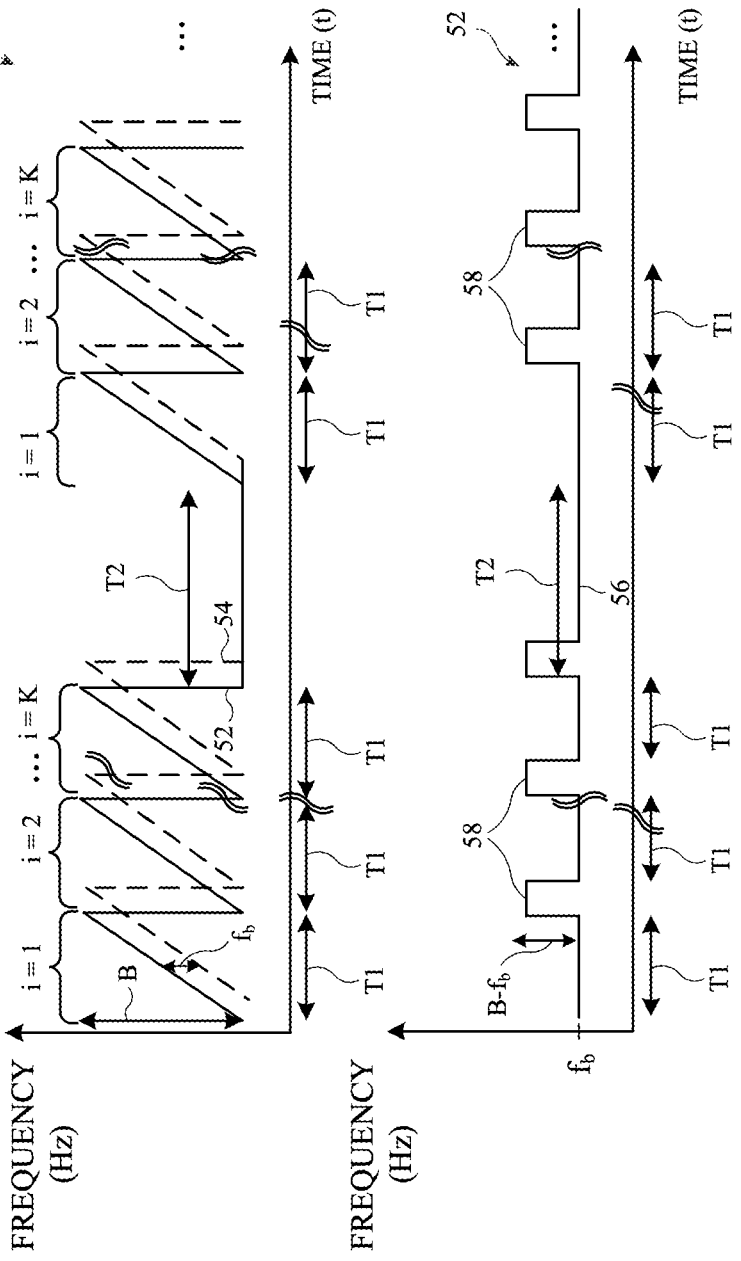


FIG. 3

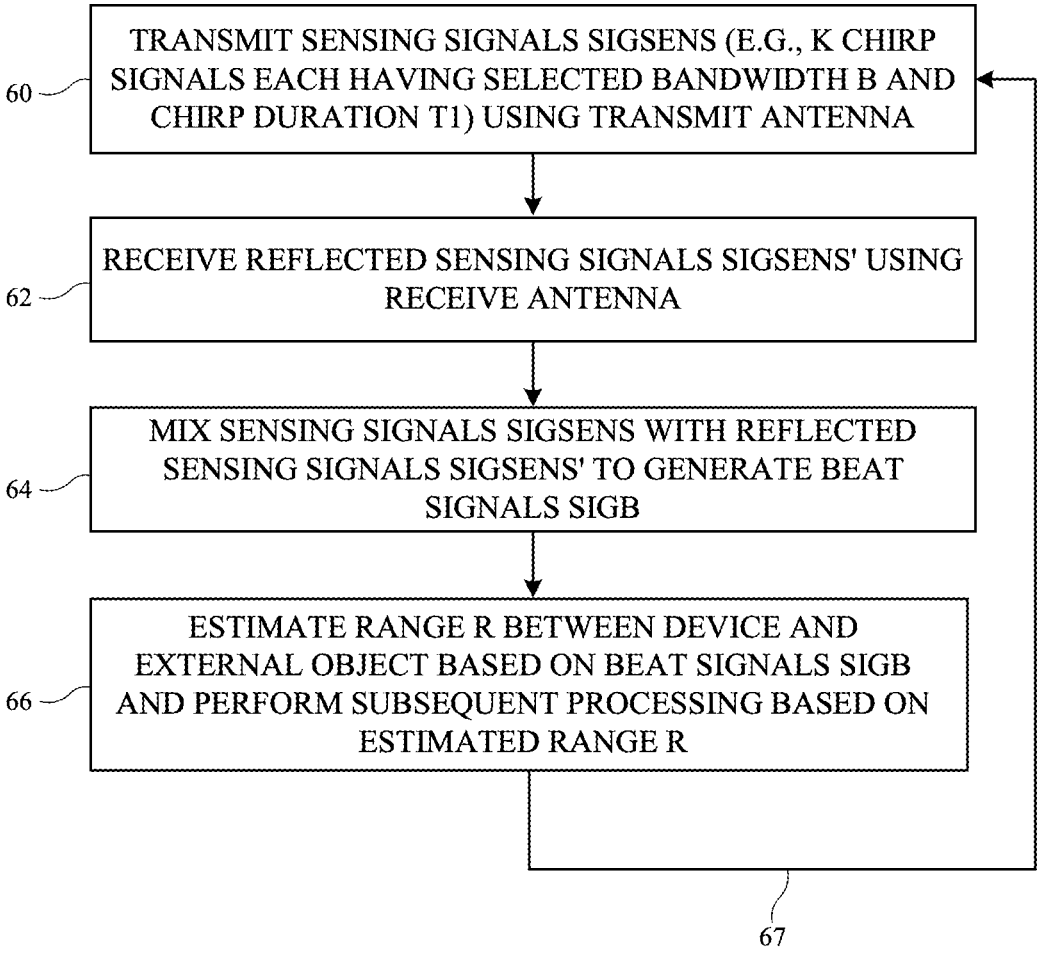

TRANSMIT SENSING SIGNALS SIGSENS (E.G., K CHIRP SIGNALS EACH HAVING SELECTED BANDWIDTH B AND CHIRP DURATION T1) USING TRANSMIT ANTENNA
60
RECEIVE REFLECTED SENSING SIGNALS SIGSENS' USING RECEIVE ANTENNA
62
MIX SENSING SIGNALS SIGSENS WITH REFLECTED SENSING SIGNALS SIGSENS' TO GENERATE BEAT SIGNALS SIGB
64
ESTIMATE RANGE R BETWEEN DEVICE AND EXTERNAL OBJECT BASED ON BEAT SIGNALS SIGB AND PERFORM SUBSEQUENT PROCESSING BASED ON ESTIMATED RANGE R
66
67

FIG. 4

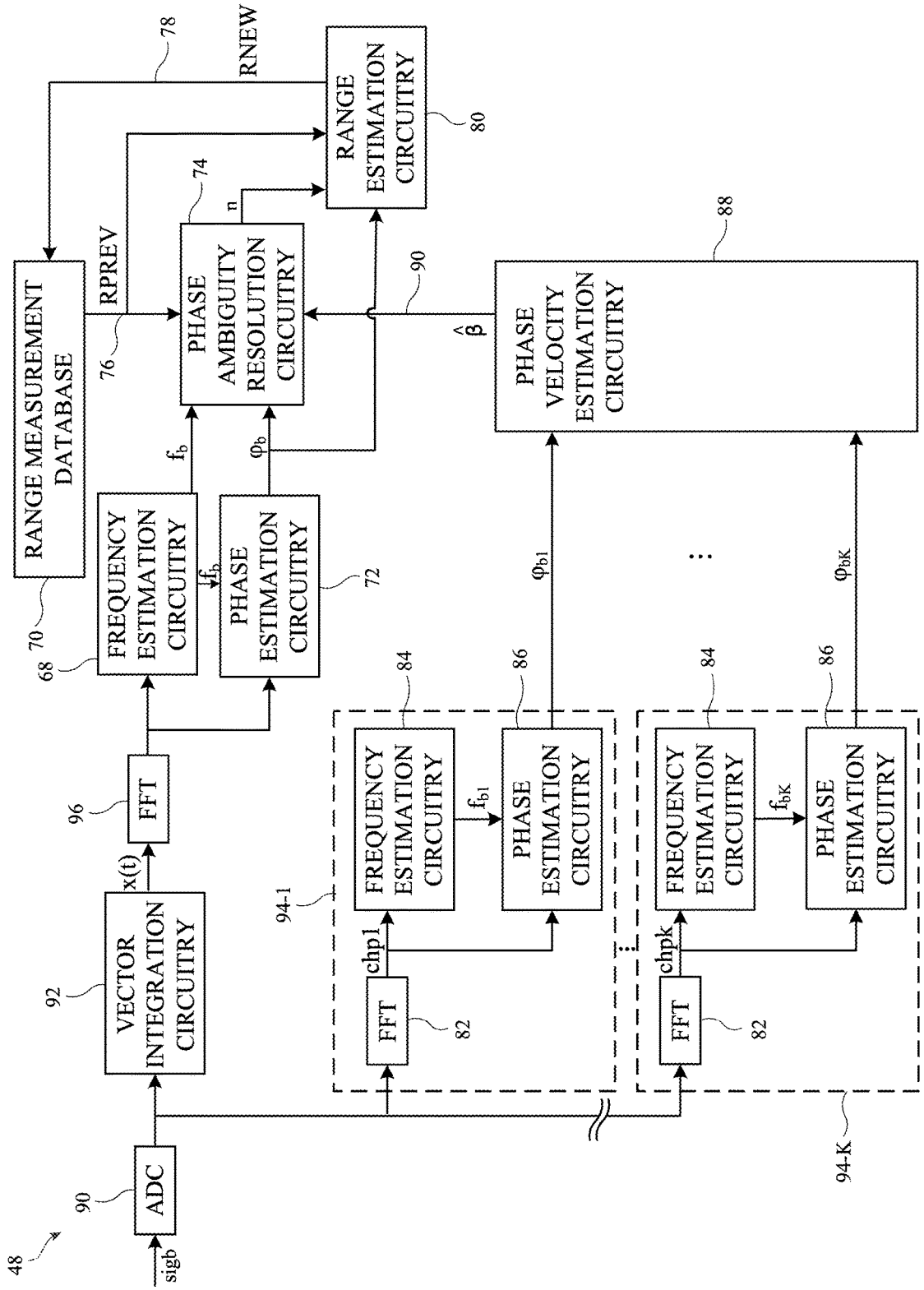

48
sigb
ADC
90
VECTOR INTEGRATION CIRCUITRY
92
x(t)
FFT
96
RANGE MEASUREMENT DATABASE
70
68
FREQUENCY ESTIMATION CIRCUITRY
PHASE ESTIMATION CIRCUITRY
72
f_b
φ_b
PHASE AMBIGUITY RESOLUTION CIRCUITRY
74
RPREV
76
RNEW
78
RANGE ESTIMATION CIRCUITRY
80
n
90
$\hat{\beta}$
PHASE VELOCITY ESTIMATION CIRCUITRY
88
94-1
FREQUENCY ESTIMATION CIRCUITRY
PHASE ESTIMATION CIRCUITRY
84
86
f_{b1}
φ_{b1}
chp1
FFT
82
94-K
f_{bK}
φ_{bK}
chpk

FIG. 5

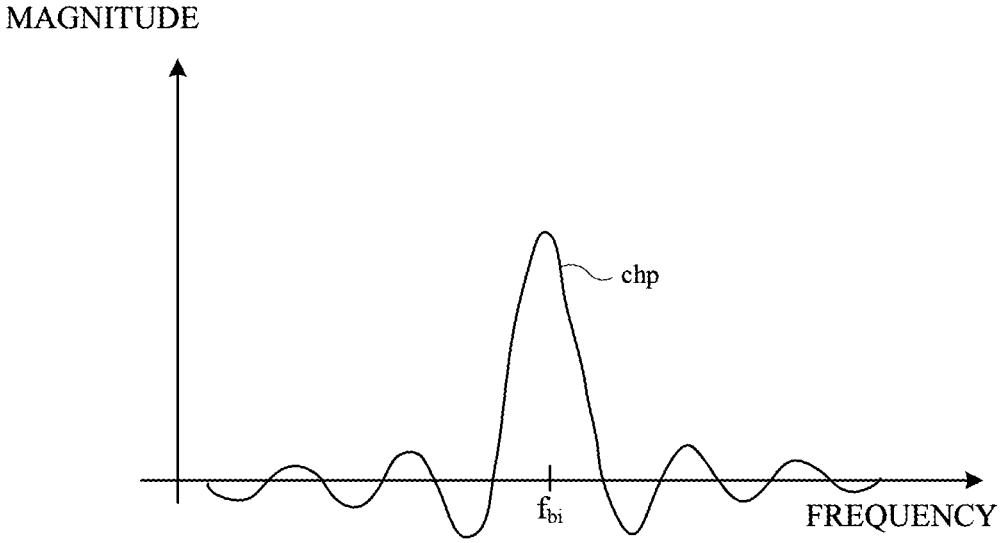


FIG. 6

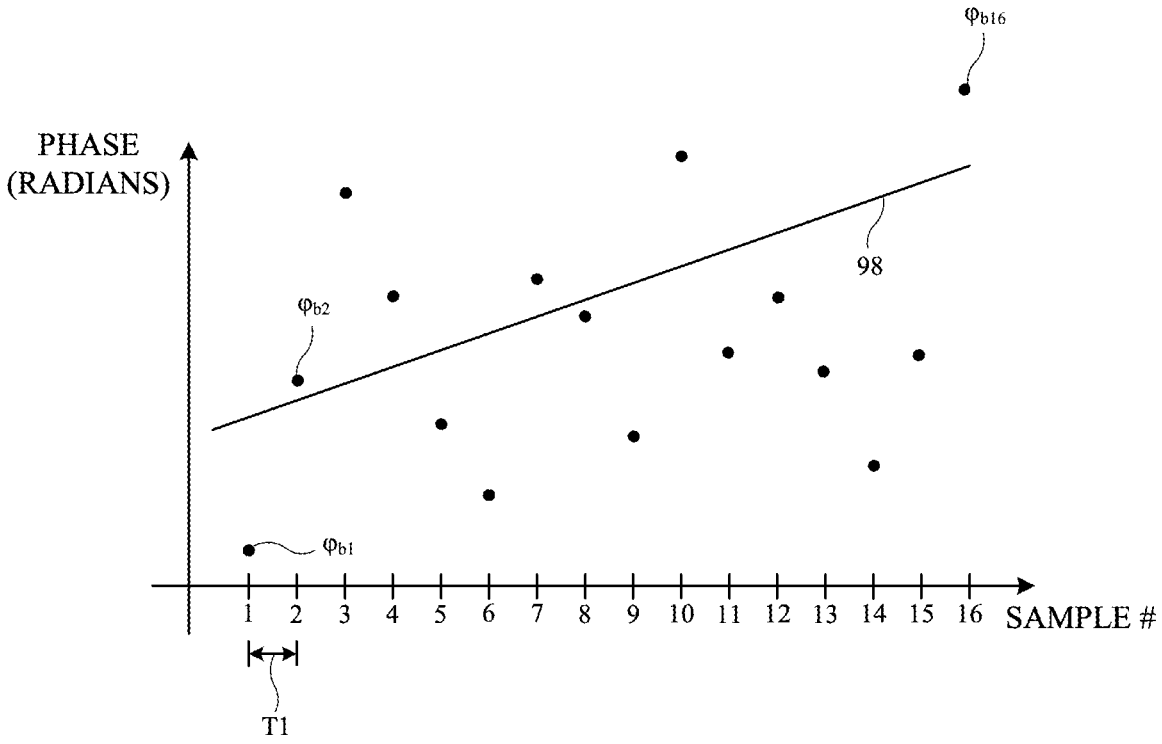

φb16
PHASE
(RADIANS)
98
φb2
φb1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
SAMPLE #
T1

FIG. 7

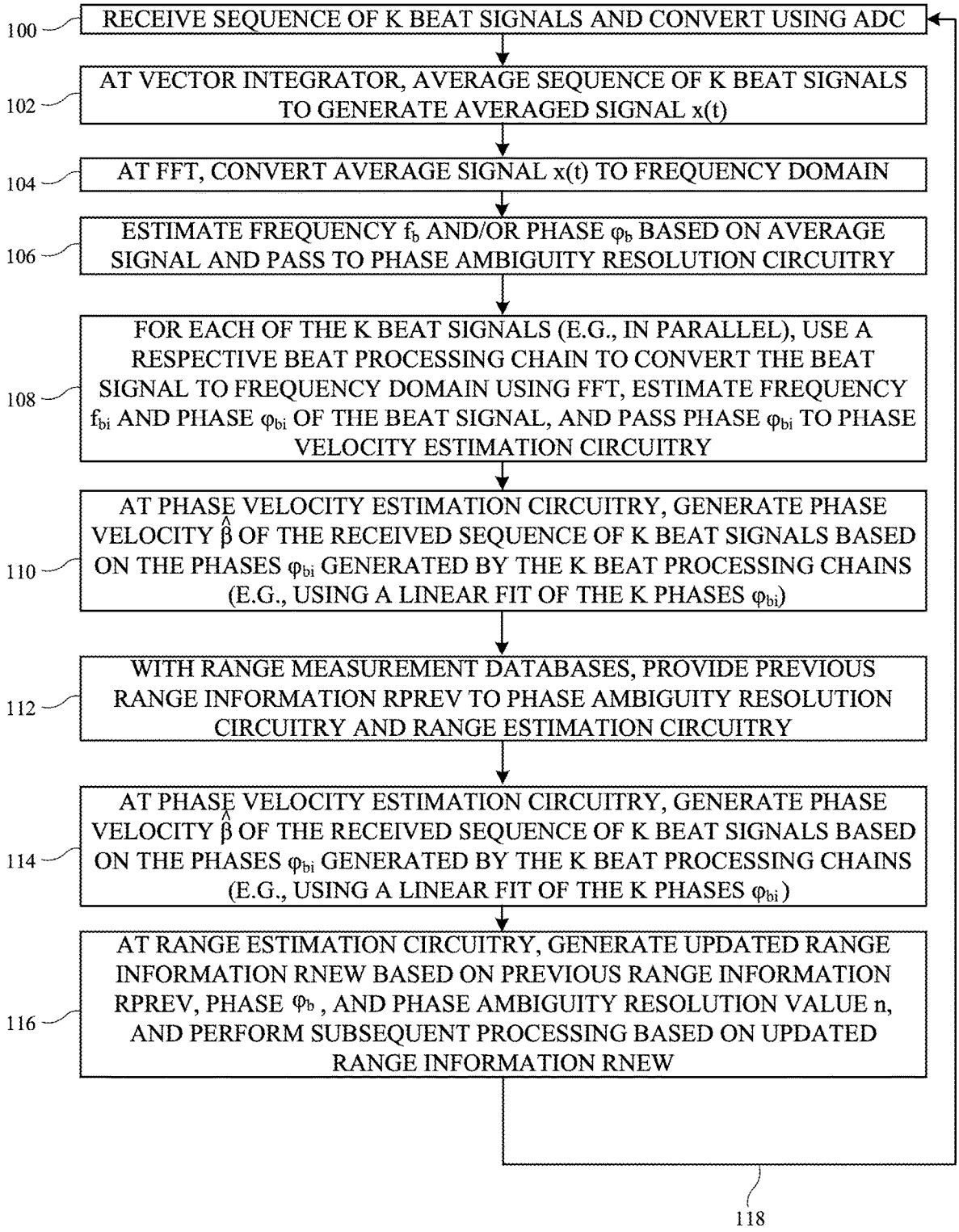

100
RECEIVE SEQUENCE OF K BEAT SIGNALS AND CONVERT USING ADC
102
AT VECTOR INTEGRATOR, AVERAGE SEQUENCE OF K BEAT SIGNALS TO GENERATE AVERAGED SIGNAL x(t)
104
AT FFT, CONVERT AVERAGE SIGNAL x(t) TO FREQUENCY DOMAIN
106
ESTIMATE FREQUENCY f_b AND/OR PHASE φ_b BASED ON AVERAGE SIGNAL AND PASS TO PHASE AMBIGUITY RESOLUTION CIRCUITRY
108
FOR EACH OF THE K BEAT SIGNALS (E.G., IN PARALLEL), USE A RESPECTIVE BEAT PROCESSING CHAIN TO CONVERT THE BEAT SIGNAL TO FREQUENCY DOMAIN USING FFT, ESTIMATE FREQUENCY f_{bi} AND PHASE φ_{bi} OF THE BEAT SIGNAL, AND PASS PHASE φ_{bi} TO PHASE VELOCITY ESTIMATION CIRCUITRY
110
AT PHASE VELOCITY ESTIMATION CIRCUITRY, GENERATE PHASE VELOCITY $\hat{\beta}$ OF THE RECEIVED SEQUENCE OF K BEAT SIGNALS BASED ON THE PHASES φ_{bi} GENERATED BY THE K BEAT PROCESSING CHAINS (E.G., USING A LINEAR FIT OF THE K PHASES φ_{bi})
112
WITH RANGE MEASUREMENT DATABASES, PROVIDE PREVIOUS RANGE INFORMATION RPREV TO PHASE AMBIGUITY RESOLUTION CIRCUITRY AND RANGE ESTIMATION CIRCUITRY
114
AT PHASE VELOCITY ESTIMATION CIRCUITRY, GENERATE PHASE VELOCITY $\hat{\beta}$ OF THE RECEIVED SEQUENCE OF K BEAT SIGNALS BASED ON THE PHASES φ_{bi} GENERATED BY THE K BEAT PROCESSING CHAINS (E.G., USING A LINEAR FIT OF THE K PHASES φ_{bi})
116
AT RANGE ESTIMATION CIRCUITRY, GENERATE UPDATED RANGE INFORMATION RNEW BASED ON PREVIOUS RANGE INFORMATION RPREV, PHASE φ_b, AND PHASE AMBIGUITY RESOLUTION VALUE n, AND PERFORM SUBSEQUENT PROCESSING BASED ON UPDATED RANGE INFORMATION RNEW
118

FIG. 8

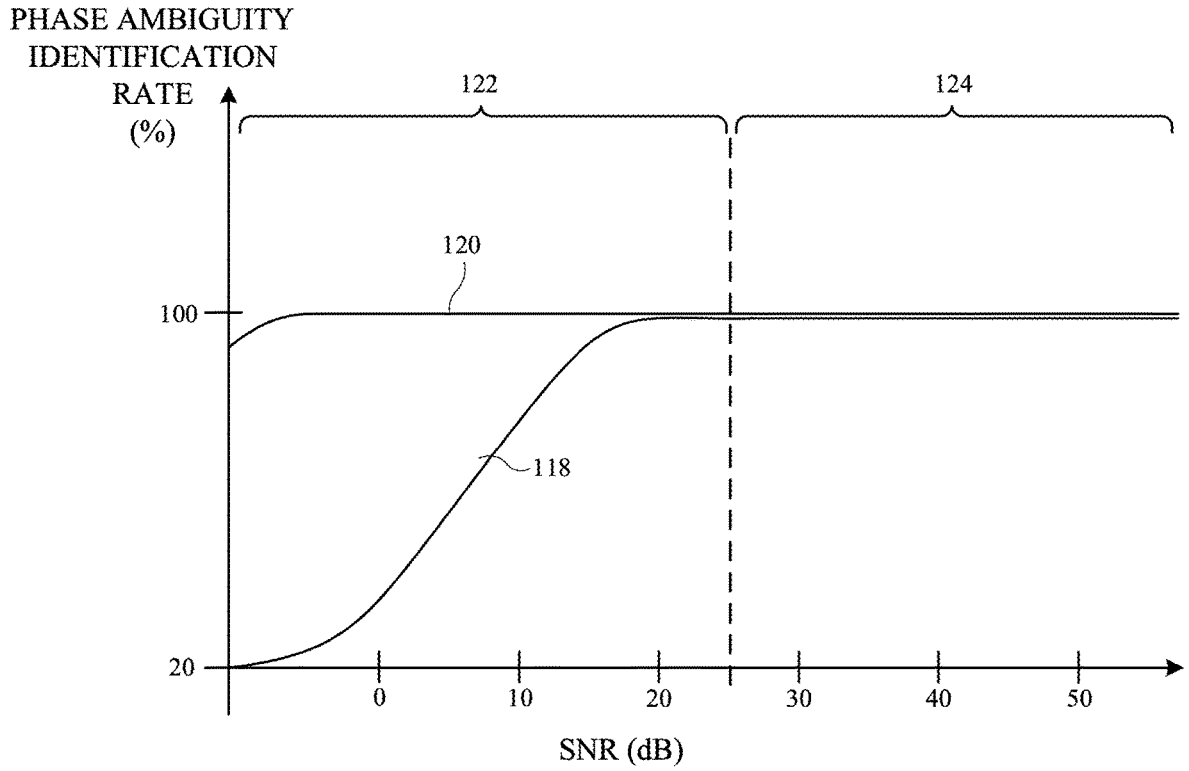

PHASE AMBIGUITY
IDENTIFICATION
RATE
(%)
122
124
120
100
118
20
0
10
20
30
40
50
SNR (dB)

FIG. 9

ELECTRONIC DEVICES WITH LOW SIGNAL-TO-NOISE RATIO RANGE MEASUREMENT CAPABILITIES

FIELD

This disclosure relates generally to electronic devices and, more particularly, to electronic devices with wireless circuitry.

BACKGROUND

Electronic devices are often provided with wireless capabilities. An electronic device with wireless capabilities has wireless circuitry that includes one or more antennas. The wireless circuitry is used to perform communications using radio-frequency signals transmitted by the antennas.

In some scenarios, the wireless circuitry is also used to perform sensing operations to detect the distance between an external object and the electronic device. It can be particularly difficult to detect this distance with high accuracy, particularly when the external object is in motion.

SUMMARY

An electronic device may include wireless circuitry controlled by one or more processors. The wireless circuitry may include communications circuitry for performing wireless communications. The wireless circuitry may include sensing circuitry having a sensing transmitter and a sensing receiver for performing sensing operations. The wireless circuitry may include a set of antennas. The sensing circuitry may transmit radio-frequency sensing signals such as chirp signals. The sensing circuitry may receive reflected radio-frequency sensing signals such as reflected chirp signals. Mixer circuitry may mix the sensing signals with the reflected sensing signals to generate a series of beat signals.

The sensing receiver may generate a beat phase based on an average of the series of beat signals. The sensing receiver may generate a set of phase values based on the series of beat signals, where each phase value in the set of phase values is generated using a respective beat signal in the series of beat signals. The sensing receiver may generate a beat phase velocity of the series of beat signals based on the set of phase values. The sensing receiver may resolve a phase ambiguity in the beat phase for identifying a range between the electronic device and an external object. For example, the sensing receiver may generate a phase ambiguity resolution value based on the phase velocity, the beat phase, and a previous beat phase generated for an earlier series of beat signals. The sensing receiver may identify the range based on the phase ambiguity resolution value, the beat phase, the previous beat phase, and a previous range value associated with the previous beat phase. Using phase velocity to resolve phase ambiguity in this way may allow the sensing circuitry to generate accurate ranges even in a low signal-to-noise ratio regime, such as when the external object is moving relative to the electronic device.

An aspect of the disclosure provides an electronic device. The electronic device can include one or more antennas configured to transmit radio-frequency sensing signals and configured to receive reflected radio-frequency sensing signals (e.g., where different antennas transmit the radio-frequency sensing signals and receive the reflected radio-frequency sensing signals or where the same antenna transmits the radio-frequency sensing signals and receives the reflected radio-frequency sensing signals). The electronic device can include a mixer configured to generate beat signals based on the radio-frequency sensing signals and the reflected radio-frequency sensing signals. The electronic device can include one or more processors configured to identify a range between the electronic device and an external object based on a beat phase of the beat signals and a beat phase velocity of the beat signals.

An aspect of the disclosure provides a method of operating an electronic device having antennas, a mixer, and one or more processors. The method can include with the mixer, generating a series of beat signals from radio-frequency sensing signals transmitted by one or more of the antennas and a reflected version of the radio-frequency sensing signals received by one or more of the antennas. The method can include with the one or more processors, generating a beat phase from an average of the series of beat signals. The method can include with the one or more processors, generating a phase velocity of the series of beat signals. The method can include with the one or more processors, generating a range value associated with a distance between the electronic device and an external object based on the beat phase and the phase velocity.

An aspect of the disclosure provides a non-transitory computer-readable storage medium storing one or more programs configured to be executed by at least one processor on an electronic device. The one or more programs can include instructions that, when executed by the at least one processor, cause the at least one processor to generate an average value of a series of beat signals associated with radio-frequency sensing signals transmitted and received by the electronic device. The one or more programs can include instructions that, when executed by the at least one processor, cause the at least one processor to generate a beat phase based on the average value. The one or more programs can include instructions that, when executed by the at least one processor, cause the at least one processor to generate a set of phase values, wherein each phase value in the set of phase values is generated based on a respective beat signal in the series of beat signals. The one or more programs can include instructions that, when executed by the at least one processor, cause the at least one processor to generate a beat phase velocity based on the set of phase values. The one or more programs can include instructions that, when executed by the at least one processor, cause the at least one processor to identify a range between the electronic device and an external object based on the beat phase and the beat phase velocity.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of an illustrative electronic device having communications circuitry for performing wireless communications using antennas and having sensing circuitry for performing sensing operations using the antennas in accordance with some embodiments.

FIG. **2** is a circuit block diagram of illustrative sensing circuitry that transmits sensing signals over a transmit antenna and that receives reflected sensing signals over a receive antenna to measure the range between an electronic device and an external object in accordance with some embodiments.

FIG. **3** includes plots of frequency as a function of time for illustrative transmitted and received sensing signals that may be mixed to produce a series of beat signals for detecting the range between an electronic device and an external object in accordance with some embodiments.

FIG. **4** is a flow chart of illustrative operations involved in measuring the range between an electronic device and an external object using sensing circuitry that transmits sensing signals and that receives reflected sensing signals in accordance with some embodiments.

FIG. **5** is a circuit block diagram of illustrative sensing circuitry having components for identifying the range between an electronic device and an external object based on the phase velocity of a series of beat signals in accordance with some embodiments.

FIG. **6** is a plot of a beat signal in the frequency domain that may be processed by an illustrative beat processing chain to generate a phase of the beat signal in accordance with some embodiments.

FIG. **7** is a plot of illustrative phases for a series of beat signals that may be processed to generate a phase velocity of the series of beat signals in accordance with some embodiments.

FIG. **8** is a flow chart of illustrative operations involved in identifying the range between an electronic device and an external object based on the phase velocity of a series of beat signals in accordance with some embodiments.

FIG. **9** is a plot of phase ambiguity identification rate as a function of signal-to-noise ratio showing how the phase velocity of a series of beat signals can optimize the performance of illustrative sensing circuitry in identifying the range between an electronic device and an external object in accordance with some embodiments.

DETAILED DESCRIPTION

Electronic device **10** of FIG. **1** may be a computing device such as a laptop computer, a desktop computer, a computer monitor containing an embedded computer, a tablet computer, a cellular telephone, a media player, or other handheld or portable electronic device, a smaller device such as a wristwatch device, a pendant device, a headphone or earpiece device, a device embedded in eyeglasses or other equipment worn on a user's head, or other wearable or miniature device, a television, a computer display that does not contain an embedded computer, a gaming device, a navigation device, an embedded system such as a system in which electronic equipment with a display is mounted in a kiosk or automobile, a wireless internet-connected voice-controlled speaker, a home entertainment device, a remote control device, a gaming controller, a peripheral user input device, a wireless base station or access point, equipment that implements the functionality of two or more of these devices, or other electronic equipment.

As shown in the functional block diagram of FIG. **1**, device **10** may include components located on or within an electronic device housing such as housing **12**. Housing **12**, which may sometimes be referred to as a case, may be formed of plastic, glass, ceramics, fiber composites, metal (e.g., stainless steel, aluminum, metal alloys, etc.), other suitable materials, or a combination of these materials. In some situations, parts or all of housing **12** may be formed from dielectric or other low-conductivity material (e.g., glass, ceramic, plastic, sapphire, etc.). In other situations, housing **12** or at least some of the structures that make up housing **12** may be formed from metal elements.

Device **10** may include control circuitry **14**. Control circuitry **14** may include storage such as storage circuitry **16**. Storage circuitry **16** may include hard disk drive storage, nonvolatile memory (e.g., flash memory or other electrically-programmable-read-only memory configured to form a solid-state drive), volatile memory (e.g., static or dynamic random-access-memory), etc. Storage circuitry **16** may include storage that is integrated within device **10** and/or removable storage media.

Control circuitry **14** may include processing circuitry such as processing circuitry **18**. Processing circuitry **18** may be used to control the operation of device **10**. Processing circuitry **18** may include on one or more processors, microprocessors, microcontrollers, digital signal processors, host processors, baseband processor integrated circuits, application specific integrated circuits, central processing units (CPUs), graphics processing units (GPUs), etc. Control circuitry **14** may be configured to perform operations in device **10** using hardware (e.g., dedicated hardware or circuitry), firmware, and/or software. Software code for performing operations in device **10** may be stored on storage circuitry **16** (e.g., storage circuitry **16** may include non-transitory (tangible) computer readable storage media that stores the software code). The software code may sometimes be referred to as program instructions, software, data, instructions, or code. Software code stored on storage circuitry **16** may be executed by processing circuitry **18**.

Control circuitry **14** may be used to run software on device **10** such as satellite navigation applications, internet browsing applications, voice-over-internet-protocol (VOIP) telephone call applications, email applications, media playback applications, operating system functions, etc. To support interactions with external equipment, control circuitry **14** may be used in implementing communications protocols. Communications protocols that may be implemented using control circuitry **14** include internet protocols, wireless local area network (WLAN) protocols (e.g., IEEE 802.11 protocols—sometimes referred to as Wi-Fi®), protocols for other short-range wireless communications links such as the Bluetooth® protocol or other wireless personal area network (WPAN) protocols, IEEE 802.11ad protocols (e.g., ultra-wideband protocols), cellular telephone protocols (e.g., 3G protocols, 4G (LTE) protocols, 3GPP Fifth Generation (5G) New Radio (NR) protocols, etc.), antenna diversity protocols, satellite navigation system protocols (e.g., global positioning system (GPS) protocols, global navigation satellite system (GLONASS) protocols, etc.), antenna-based spatial ranging protocols, or any other desired communications protocols. Each communications protocol may be associated with a corresponding radio access technology (RAT) that specifies the physical connection methodology used in implementing the protocol.

Device **10** may include input-output circuitry **20**. Input-output circuitry **20** may include input-output devices **22**. Input-output devices **22** may be used to allow data to be supplied to device **10** and to allow data to be provided from device **10** to external devices. Input-output devices **22** may include user interface devices, data port devices, and other input-output components. For example, input-output devices **22** may include touch sensors, displays (e.g., touch-sensitive and/or force-sensitive displays), light-emitting components such as displays without touch sensor capabilities, buttons (mechanical, capacitive, optical, etc.), scrolling wheels, touch pads, key pads, keyboards, microphones, cameras, buttons, speakers, status indicators, audio jacks and other audio port components, digital data port devices, motion sensors (accelerometers, gyroscopes, and/or compasses that detect motion), capacitance sensors, proximity sensors, magnetic sensors, force sensors (e.g., force sensors coupled to a display to detect pressure applied to the display), temperature sensors, etc. In some configurations, keyboards, headphones, displays, pointing devices such as trackpads, mice, and joysticks, and other input-output devices may be

coupled to device **10** using wired or wireless connections (e.g., some of input-output devices **22** may be peripherals that are coupled to a main processing unit or other portion of device **10** via a wired or wireless link).

Input-output circuitry **20** may include wireless circuitry **24** to support wireless communications and radio-based sensing operations. Wireless circuitry **24** (sometimes referred to herein as wireless communications circuitry **24**) may include two or more antennas **30**. Wireless circuitry **24** may also include baseband processor circuitry, transceiver circuitry, amplifier circuitry, filter circuitry, switching circuitry, analog-to-digital converter (ADC) circuitry, digital-to-analog converter (DAC) circuitry, radio-frequency transmission lines, and/or any other circuitry for transmitting and/or receiving radio-frequency signals using antennas **30**.

Antennas **30** may be formed using any desired antenna structures for conveying radio-frequency signals. For example, antennas **30** may include antennas with resonating elements that are formed from loop antenna structures, patch antenna structures, inverted-F antenna structures, slot antenna structures, planar inverted-F antenna structures, helical antenna structures, monopole antennas, dipoles, hybrids of these designs, etc. Filter circuitry, switching circuitry, impedance matching circuitry, and/or other antenna tuning components may be adjusted to adjust the frequency response and wireless performance of antennas **30** over time. If desired, two or more of antennas **30** may be integrated into a phased antenna array (sometimes referred to herein as a phased array antenna) in which each of the antennas conveys radio-frequency signals with a respective phase and magnitude that is adjusted over time so the radio-frequency signals constructively and destructively interfere to produce a signal beam in a given pointing direction. The term "convey radio-frequency signals" as used herein means the transmission and/or reception of the radio-frequency signals (e.g., for performing unidirectional and/or bidirectional wireless communications with external wireless communications equipment). Antennas **30** may transmit the radio-frequency signals by radiating the radio-frequency signals into free space (or to free space through intervening device structures such as a dielectric cover layer). Antennas **30** may additionally or alternatively receive the radio-frequency signals from free space (e.g., through intervening devices structures such as a dielectric cover layer). The transmission and reception of radio-frequency signals by antennas **30** each involve the excitation or resonance of antenna currents on an antenna resonating element in the antenna by the radio-frequency signals within the frequency band(s) of operation of the antenna.

Wireless circuitry **24** may include communications circuitry **26** (sometimes referred to herein as wireless communications circuitry **26**) for transmitting and/or receiving wireless communications data using antennas **30**. Communications circuitry **26** may include baseband circuitry (e.g., one or more baseband processors) and one or more radios (e.g., radio-frequency transceivers, modems, etc.) for conveying radio-frequency signals using one or more antennas **30**. Communications circuitry **26** may use antennas **30** to transmit and/or receive radio-frequency signals that convey the wireless communications data between device **10** and external wireless communications equipment (e.g., one or more other devices such as device **10**, a wireless access point or base station, etc.). The wireless communications data may be conveyed bidirectionally or unidirectionally. The wireless communications data may, for example, include data that has been encoded into corresponding data packets such as wireless data associated with a telephone call, streaming media content, internet browsing, wireless data associated with software applications running on device **10**, email messages, etc.

Communications circuitry **26** may transmit and/or receive radio-frequency signals within corresponding frequency bands at radio frequencies (sometimes referred to herein as communications bands or simply as "bands"). The frequency bands handled by communications circuitry **26** may include wireless local area network (WLAN) frequency bands (e.g., Wi-Fi® (IEEE 802.11) or other WLAN communications bands) such as a 2.4 GHz WLAN band (e.g., from 2400 to 2480 MHz), a 5 GHz WLAN band (e.g., from 5180 to 5825 MHz), a Wi-Fi® 6E band (e.g., from 5925-7125 MHz), and/or other Wi-Fi® bands (e.g., from 1875-5160 MHz), wireless personal area network (WPAN) frequency bands such as the 2.4 GHz Bluetooth® band or other WPAN communications bands, cellular telephone frequency bands (e.g., bands from about 600 MHz to about 5 GHz, 3G bands, 4G LTE bands, 5G New Radio Frequency Range 1 (FR1) bands below 10 GHz, 5G New Radio Frequency Range 2 (FR2) bands between 20 and 60 GHz, etc.), other centimeter or millimeter wave frequency bands between 10-300 GHz, near-field communications frequency bands (e.g., at 13.56 MHz), satellite navigation frequency bands (e.g., a GPS band from 1565 to 1610 MHz, a Global Navigation Satellite System (GLONASS) band, a BeiDou Navigation Satellite System (BDS) band, etc.), ultra-wideband (UWB) frequency bands that operate under the IEEE 802.15.4 protocol and/or other ultra-wideband communications protocols, communications bands under the family of 3GPP wireless communications standards, communications bands under the IEEE 802.XX family of standards, and/or any other desired frequency bands of interest.

In addition to conveying wireless communications data, wireless circuitry **24** may also use antennas **30** to perform radio-frequency sensing operations (sometimes referred to herein as radio-based sensing operations or simply as sensing operations). The sensing operations may allow device **10** to detect (e.g., sense or identify) the presence, location, orientation, and/or velocity (motion) of objects external to device **10**. Detecting, sensing, or identifying the presence, location, orientation, and/or velocity (motion) of an external object at any given time or over a given time period may sometimes be referred to herein simply as detecting the external object or performing spatial ranging operations. The sensing operations may be performed over a relatively short range such as ranges of a few cm from antennas **30** (e.g., using voltage standing wave ratio detector(s) coupled to antennas **30**) or over longer ranges such as ranges of dozens of cm, a few meters, dozens of meters, etc. In one implementation that is described herein as an example, the sensing operations may detect the location of the external object as the distance (sometimes referred to herein as range R) between device **10** (e.g., antennas **30**) and the external object.

Control circuitry **14** may use the detected presence, location, orientation, and/or velocity of the external objects to perform any desired device operations. As examples, control circuitry **14** may use the detected presence, location (e.g., range R), orientation, and/or velocity of the external objects to identify a corresponding user input for one or more software applications running on device **10** such as a gesture input performed by the user's hand(s) or other body parts or performed by an external stylus, gaming controller, head-mounted device, or other peripheral devices or accessories, to determine when one or more antennas **30** needs to be disabled or provided with a reduced maximum transmit

power level (e.g., for satisfying regulatory limits on radio-frequency exposure), to determine how to steer a radio-frequency signal beam produced by antennas **30** for communications circuitry **26** (e.g., in scenarios where antennas **30** include a phased array of antennas **30**), to map or model the environment around device **10** (e.g., to produce a software model of the room where device **10** is located for use by an augmented reality application, gaming application, map application, home design application, engineering application, etc.), to detect the presence of obstacles in the vicinity of (e.g., around) device **10** or in the direction of motion of the user of device **10**, etc.

Wireless circuitry **24** may include sensing circuitry **28** for performing sensing operations using antennas **30**. Sensing circuitry **28** may include a sensing transmitter (e.g., transmitter circuitry including signal generators, synthesizers, etc.), a sensing receiver, mixer circuitry, amplifier circuitry, filter circuitry, baseband circuitry, ADC circuitry, DAC circuitry, and/or any other desired components used in performing sensing operations using antennas **30**. Sensing circuitry **28** may perform the sensing operations using radio-frequency sensing signals that are transmitted by antennas **30** and using reflected versions of the radio-frequency sensing signals that have reflected off external objects around device **10** (e.g., using a frequency-modulated continuous-wave (FMCW) scheme, a full-duplex ranging scheme, etc.). Antennas **30** may include separate antennas for conveying wireless communications data for communications circuitry **26** and for conveying sensing signals or may include one or more antennas **30** that are used to both convey wireless communications data and to perform sensing operations. Using a single antenna **30** to both convey wireless communications data and perform sensing operations may, for example, serve to minimize the amount of space occupied in device **10** by antennas **30**.

Sensing circuitry **28** may be coupled to antennas **30** over at least two radio-frequency transmission line paths **32**. Communications circuitry **26** may be coupled to antennas **30** over at least one radio-frequency transmission line path **32**. Separate radio-frequency transmission line paths **32** may couple sensing circuitry **28** and communications circuitry **26** to antennas **30** (e.g., as shown in FIG. **1**) or one or more radio-frequency transmission line paths **32** may couple one or more antennas **30** to both sensing circuitry **28** and communications circuitry **26**. Radio-frequency transmission line paths **32** may include coaxial cables, microstrip transmission lines, stripline transmission lines, edge-coupled microstrip transmission lines, edge-coupled stripline transmission lines, transmission lines formed from combinations of transmission lines of these types, etc. Radio-frequency transmission line paths **32** may be integrated into rigid and/or flexible printed circuit boards if desired. Radio-frequency front end (RFFE) modules may be interposed on one or more radio-frequency transmission line paths **32**. The radio-frequency front end modules may include substrates, integrated circuits, chips, or packages that are separate from sensing circuitry **28** and communications circuitry **26** and may include filter circuitry, switching circuitry, amplifier circuitry, impedance matching circuitry, radio-frequency coupler circuitry, and/or any other desired radio-frequency circuitry for operating on the radio-frequency signals conveyed over radio-frequency transmission line paths **32**.

The example of FIG. **1** is merely illustrative. While control circuitry **14** is shown separately from wireless circuitry **24** in the example of FIG. **1** for the sake of clarity, wireless circuitry **24** may include processing circuitry (e.g., one or more processors) that forms a part of processing circuitry **18** and/or storage circuitry that forms a part of storage circuitry **16** of control circuitry **14** (e.g., portions of control circuitry **14** may be implemented on wireless circuitry **24**). As an example, control circuitry **14** may include baseband circuitry (e.g., one or more baseband processors), digital control circuitry, analog control circuitry, and/or other control circuitry that forms part of communications circuitry **26** and/or sensing circuitry **28**. The baseband circuitry may, for example, access a communication protocol stack on control circuitry **14** (e.g., storage circuitry **20**) to: perform user plane functions at a PHY layer, MAC layer, RLC layer, PDCP layer, SDAP layer, and/or PDU layer, and/or to perform control plane functions at the PHY layer, MAC layer, RLC layer, PDCP layer, RRC, layer, and/or non-access stratum layer. If desired, the PHY layer operations may additionally or alternatively be performed by radio-frequency (RF) interface circuitry in wireless circuitry **24**.

FIG. **2** is a circuit block diagram showing one example of the components that may be included in sensing circuitry **28**. As shown in FIG. **2**, sensing circuitry **28** may include at least one sensing transmitter **34** and at least one sensing receiver **48**. Sensing transmitter **34** may be coupled to a first antenna **30** such as antenna **30**TX (sometimes referred to herein as transmit antenna **30**TX) over radio-frequency transmission line path **32**TX (sometimes referred to herein as transmit path **32**TX). Sensing receiver **48** may be coupled to a second antenna **30** such as antenna **30**RX (sometimes referred to herein as receive antenna **30**RX) over radio-frequency transmission line path **32**RX (sometimes referred to herein as receive path **32**RX). Transmit antenna **30**TX may also be used to transmit and/or receive radio-frequency signals that convey wireless communications data for communications circuitry **26** (FIG. **1**) if desired. Similarly, receive antenna **30**RX may also be used to transmit and/or receive radio-frequency signals that convey wireless communications data for communications circuitry **26** if desired. The transmit antenna and the receive antenna may be the same antenna or portions of the same antenna if desired. One or more power amplifiers may be interposed on transmit path **32**TX. One or more low noise amplifiers may be interposed on receive path **32**RX.

Sensing transmitter **34** may transmit radio-frequency sensing signals sigsens over transmit path **32**TX and transmit antenna **30**TX. Sensing signals sigsens may include any desired signals for performing spatial ranging operations (e.g., chirp signals, one or more tones, continuous waves of radio-frequency energy, etc.). Sensing signals sigsens may be transmitted using any desired carrier frequencies (e.g., frequencies greater than 10 GHz, greater than 20 GHz, less than 60 GHz, less than 10 GHz, less than 6 GHz, less than 1 GHz, etc.). An implementation in which sensing signals sigsens include chirp signals is described herein as an example. Chirp signals include frequency ramps (sometimes referred to as chirps) that periodically ramp-up over time. In this example, sensing transmitter **34** may include a signal generator or synthesizer such as signal generator **36** (e.g., a digital chirp generator). Signal generator **36** may generate the chirp signals and may provide the chirp signals to DAC **38**. DAC **38** may convert the chirp signals to the analog domain and may provide the analog chirp signals to mixer **40**. Mixer **40** may up-convert the analog chirp signals to radio frequencies (as sensing signals sigsens) using a clocking signal such as a local oscillator signal produced by local oscillator (LO) **42**. Antenna **30**TX may radiate sensing signals sigsens as radio-frequency signals **47**. Unlike the radio-frequency signals transmitted by communications cir-

cuitry **26** of FIG. **1**, sensing signals sigsens and radio-frequency signals **47** may be free from wireless communications data (e.g., cellular communications data packets, WLAN communications data packets, etc.).

Radio-frequency signals **47** may reflect off objects external to device **10**, such as external object **45**, as reflected signals **49**. External object **45** may be, for example, the ground, a building, part of a building, a wall, furniture, a ceiling, a person, a body part (e.g., the head, hand, or other body part of the user of device **10** or other humans in the vicinity of device **10**), an animal, a vehicle, a landscape or geographic feature, an obstacle, external communications equipment, another device of the same type as device **10** or a peripheral/accessory device such as a gaming controller, stylus (e.g., for providing input to a touch and/or force-sensitive display on device **10**), or remote control, or any other physical object or entity that is external to device **10**.

As shown in FIG. **2**, sensing circuitry **28** may include a mixer such as mixer **46**. Mixer **46** may have a first input coupled to transmit path **32**TX over de-chirp path **44** and may have a second input coupled to receive path **32**RX. The output of mixer **46** may be coupled to the input of sensing receiver **48**. Mixer **46** may sometimes be referred to herein as de-chirp mixer **46**. Receive antenna **30**RX may receive reflected signals **49** (e.g., a reflected version of radio-frequency signals **47** that has reflected off external object **45**) and may pass the reflected signals to mixer **46** in sensing circuitry **24** over receive path **32**RX (e.g., as reflected sensing signals sigsens'). Reflected sensing signals sigsens' may include sensing signals sigsens (e.g., chirp signals) that have reflected off external object **45** and that have been received by receive antenna **30**RX. Transmit path **32**TX may include a coupler or signal splitter that couples some of the sensing signals sigsens on transmit path **32**TX onto de-chirp path **44**. If desired, one or more amplifiers (not shown) may be interposed on de-chirp path **44** to boost the amplitude of the sensing signals sigsens provided to de-chirp mixer **46**.

De-chirp mixer **46** may receive reflected sensing signals sigsens' at its second input (e.g., from receive path **32**RX). De-chirp mixer **46** may mix the sensing signals sigsens received at its first input (over de-chirp path **44**) with the reflected sensing signals sigsens' received at its second input (over receive path **32**RX) to produce or generate baseband signals sigb. Baseband signals sigb may correspond to beats associated with the difference in phase between the transmitted sensing signals sigsens and the received reflected sensing signals sigsens'. Baseband signals sigb may therefore sometimes be referred to herein as beat signals sigb.

Sensing receiver **48** may receive beat signals sigb from de-chirp mixer **46**. Sensing receiver **48** may process beat signals sigb to identify/detect the presence, location, orientation, and/or velocity of external object **45** (FIG. **3**). In one implementation that is described herein as an example, sensing receiver **48** may process beat signals sigb to identify the range R between device **10** and external object **45**.

The example of FIG. **2** is merely illustrative. If desired, de-chirp mixer **46** may be formed as a part of sensing receiver **48**. If desired, the second input of de-chirp mixer **46** may be coupled to the output of an ADC in sensing receiver **48** and de-chirp path **44** may be coupled to the input of DAC **38**. Other sensing circuitry (spatial ranging) architectures may be used if desired.

FIG. **3** includes plots of frequency as a function of time (t) for one example of the sensing signals and beat signals handled by sensing circuitry **28**. Curve **52** of plot **50** plots illustrative chirp signals that may be transmitted as sensing signals sigsens. Curve **54** of plot **50** plots illustrative reflected chirp signals that may be received by de-chirp mixer **46** in reflected sensing signals sigsens'.

As shown by curve **52**, the chirp signals in sensing signals sigsens may include periodic linear frequency ramps or chirps. Each ramp (chirp) has a bandwidth B and lasts for a chirp duration T**1** (e.g., each chirp has a slope equal to B/T**1**). Sensing transmitter **34** may transmit a series of K chirps (e.g., a first chirp i=1 during a first chirp duration T**1**, a second chirp i=2 during a second chirp duration T**1**, a Kth chirp i=K during a Kth chirp duration T**1**, etc.) for use in identifying the range R between device **10** and external object **45**.

As shown by curve **54**, the received reflected chirp signals are offset from the transmitted chirp signals in time due to the propagation of the chirp signals over-the-air in reflecting off of external object **45**. This causes the received reflected chirp signals to also be offset from the transmitted chirp signals by frequency difference f_b. De-chirp mixer **46** may mix the chirp signals associated with curve **52** with the chirp signals associated with curve **54** to generate beat signals sigb.

Curve **58** of plot **52** plots illustrative beat signals sigb that may be produced by de-chirp mixer **46** by mixing the chirp signals associated with curve **52** with the chirp signals associated with curve **54**. As shown by curve **58**, beat signals sigb are at a beat frequency that is equal to frequency difference f_b. Frequency different f_b may therefore sometimes be referred to herein as beat frequency f_b. Beat signals sigb may also include pulses of bandwidth B−f_b for each chirp duration T**1** (e.g., due to the transition from the maximum value at the end of each chirp signal to the minimum value at the beginning of the next chirp signal). In other words, de-chirp mixer **46** may produce K beat signals sigb from the K chirp signals transmitted in sensing signals sigsens and the K reflected chirp signals received in reflected sensing signals sigsens'. Sensing receiver **48** may process the K beat signals sigb to identify range R between device **10** and external object **45**.

Once the Kth chirp signal has been transmitted, a subsequent series of K chirp signals may be transmitted after a time period T**2** has elapsed (e.g., as shown by curve **52** of plot **50**). Time period T**2** may, for example, allow processing time for sensing receiver **48** to identify range R based on beat signals sigb and/or may help to reduce power consumption on device **10**. Sensing receiver **48** may use the subsequent series of K chirp signals, the K corresponding reflected chirp signals, and the K corresponding beat signals sigb to identify range R again (e.g., to track whether external object **45** has moved relative to device **10** between the first series of K chirps and the second series of K chirps). Sensing receiver **48** may store each range R value that is produced (e.g., to track the location of external object **45** relative to device **10** over time). This process may repeat any desired number of times to allow sensing circuitry **28** to continue to gather measurements of range R over time. The example of FIG. **3** is merely illustrative. Other waveforms may be used in sensing signals sigsens if desired. In other words, curves **52** and **54** of plot **50** may have other shapes. Curve **58** of plot **52** may have other shapes in practice.

FIG. **4** is a flow chart of illustrative operations involved in using sensing circuitry **28** to identify range R. At operation **60**, sensing transmitter **34** (FIG. **2**) may transmit sensing signals sigsens over transmit antenna **30**TX. Sensing signals sigsens may, for example, include the K chirp signals associated with curve **52** of FIG. **3**.

At operation **62**, receive antenna **30**RX may receive reflected sensing signals sigsens'. Reflected sensing signals

sigsens' may, for example, include the K reflected chirp signals associated with curve **54** of FIG. **3**.

At operation **64**, de-chirp mixer **46** may mix the reflected sensing signals sigsens' with the transmitted sensing signals sigsens to generate (e.g., produce, output, etc.) beat signals sigb. Beat signals sigb may, for example, include the K beat signals sigb associated with curve **58** of FIG. **3**.

At operation **66**, sensing receiver **48** may estimate (e.g., generate, determine, identify, produce, output, compute, calculate, etc.) the range R between device **10** and external object **45** based on beat signals sigb (e.g., the K beat signals sig associated with curve **58** of FIG. **3**). Sensing circuitry **28** may store range R (e.g., in a range measurement database) for subsequent processing. Control circuitry **14** may perform any desired processing operations based on range R. As examples, control circuitry **14** may use range R to identify a corresponding user input for one or more software applications running on device **10** such as a gesture input performed by the user's hand(s) or other body parts or performed by an external stylus, gaming controller, head-mounted device, or other peripheral devices or accessories, to determine when one or more antennas **30** needs to be disabled or provided with a reduced maximum transmit power level (e.g., when the one or more antennas **30** is being blocked by or is in close proximity to a human body part), to determine how to steer a radio-frequency signal beam produced by antennas **30** for communications circuitry **26** (e.g., to steer a signal beam formed by the antennas around external object **45** and/or towards external communications equipment), to map or model the environment around device **10** (e.g., to produce a software model of the room where device **10** is located for use by an augmented reality application, gaming application, map application, home design application, engineering application, etc.), to detect the presence of obstacles in the vicinity of (e.g., around) device **10** or in the direction of motion of the user of device **10**, etc.

Processing may subsequently loop back to operation **60** via path **67** and sensing circuitry **28** may transmit the next series of K chirp signals. This may allow device **10** to continue to track range R and thus the location of external object **45** over time. Operation **66** may, for example, be performed during a corresponding time period T2 between the transmission of different series of K chirp signals (e.g., between iterations of operations **60**-**62**). Operations **60**, **62**, and/or **64** may be performed concurrently.

FIG. **5** is a circuit block diagram of sensing receiver **48**. As shown in FIG. **5**, sensing receiver **48** may include an ADC such as ADC **90**, vector integration circuitry **92**, fast Fourier transform (FFT) circuitry such as FFT **96**, frequency estimation circuitry **68**, phase estimation circuitry **72**, phase ambiguity resolution circuitry **74**, range measurement database **70**, range estimation circuitry **80**, phase velocity estimation circuitry **88**, and K beat processing chains **94** (e.g., a first beat processing chain **94**-**1**, a Kth beat processing chain **94**-K, etc.). Each of the K beat processing chains **94** may include respective FFT circuitry such as FFT **82**, frequency estimation circuitry **84**, and phase estimation circuitry **86**.

Vector integration circuitry **92** may sometimes be referred to herein as vector integrator **92** or vector integration engine **92**. Frequency estimation circuitry **68** and frequency estimation circuitry **84** may sometimes each be referred to herein as a frequency estimator, frequency generator, frequency generation circuitry, or frequency estimation engine. Phase estimation circuitry **72** and phase estimation circuitry **86** may sometimes each be referred to herein as a phase estimator, phase generator, phase generation circuitry, or phase estimation engine. Phase ambiguity resolution circuitry **74** may sometimes be referred to herein as phase ambiguity resolver **74**, phase ambiguity solver **74**, phase ambiguity resolution engine **74**, phase ambiguity solving engine **74**, or phase ambiguity solving circuitry **74**. Range estimation circuitry **80** may sometimes be referred to herein as range estimator **80** or range estimation engine **80**. Beat processing chains **94** may sometimes be referred to herein as beat processing circuits **94**, beat phase estimator circuits **94**, or beat phase estimator chains **94**. Phase velocity estimation circuitry **88** may sometimes be referred to herein as phase velocity estimator **88**, phase velocity generator **88**, phase velocity estimation engine **88**, or phase velocity generation circuitry **88**.

Range measurement database **70** may be hard-coded or soft-coded into sensing receiver **48** (e.g., in storage circuitry **16** of FIG. **1**) and may include a database, data table, or any other desired data structure. Range measurement database **70** may store the range values R generated by sensing receiver **48** as well as corresponding phase measurements (e.g., beat phases) generated by sensing receiver **48**, as examples. The entries of range measurement database **70** may be populated and updated during the operation of device **10** over time (e.g., as new range values R are generated). Vector integrator **92**, FFT **96**, frequency estimator **68**, phase estimator **72**, phase ambiguity resolver **74**, range estimator **80**, beat processing chains **94** (e.g., FFTs **82**, frequency estimators **84**, and phase estimators **86**), and phase velocity estimator **88** may be implemented in software (e.g., running on storage circuitry and executed by one or more processors) and/or in hardware (e.g., using one or more logic gates, adders, subtractors, multipliers, dividers, other circuit components, diodes, transistors, switches, arithmetic logic units (ALUs), registers, application-specific integrated circuits, field-programable gate arrays, one or more processors, look-up tables, etc.). Some or all of these components may form part of control circuitry **14** of FIG. **1**, for example.

As shown in FIG. **5**, ADC **90** may have an input that receives beat signal sigb (e.g., from de-chirp mixer **46** of FIG. **2**). The output of ADC **90** may be coupled to the input of vector integrator **92**. The K beat processing chains **94** may be coupled in parallel between the output of ADC **90** and the input of phase velocity estimation circuitry **88** (e.g., the output of ADC **90** may be coupled to the inputs of beat processing chains **94**). The output of vector integrator **92** may be coupled to the input of FFT **96**. The output of FFT **96** may be coupled to the input of frequency estimator **68** and to an input of phase estimator **72**. The output of frequency estimator **68** may be coupled to an input of phase estimator **72** and to an input of phase ambiguity resolver **74**. The output of phase estimator **72** may be coupled to an input of phase ambiguity resolver **74** and to an input of range estimator **80**. Range measurement database **70** may be coupled to an input of phase ambiguity resolver **74** and to an input of range estimator **80** over path **76**. The output of phase ambiguity resolver **74** may also be coupled to an input of range estimator **80**. Range estimator **80** may have an output coupled to range measurement database **70** (e.g., over path **78**) and/or outputs coupled to other portions of control circuitry **14** (FIG. **1**). Any desired paths may be used to couple the components of FIG. **5** together (e.g., signal paths, data paths, control paths, data buses, logical/virtual paths defined in software, etc.).

When sensing receiver **48** receives beat signals sigb (e.g., a series of K beat signals as shown by curve **58** of FIG. **3**), ADC **90** may convert the beat signals sigb to the digital domain.

Sensing receiver **48** may receive beat signals sigb during operations **64-66** of FIG. **4**, for example. ADC **90** may provide the digital beat signals to vector integrator **92** and to beat processing chains **94** for identifying range R based on the series of K beat signals.

Vector integrator **92** may average each of the K beat signals received from ADC **90** together to generate (e.g., calculate, compute, output, produce, etc.) time-averaged signals x(t) (e.g., by performing vector integration on the K beat signals). Averaged signals x(t) may be represented mathematically by equation 1, for example.

$$x(t)=Ae^{j(2\pi f_b t+\phi_b)} \quad (1)$$

In equation 1, A is a scalar amplitude, j is the square root of −1, t is time, and ϕ_b is the phase of averaged signals x(t). ϕ_b may sometimes be referred to herein as beat phase ϕ_b (e.g., the phase of the averaged beat signals). Averaging the K beat signals may serve to improve the signal-to-noise ratio (SNR) of the phase measurement used for identifying range R, for example. Longer integration times are generally associated with higher SNR and shorter integration times are generally associated with lower SNR, particularly when external object **45** is moving. Vector integrator **92** may provide averaged signals x(t) to FFT **96**.

FFT **96** may convert averaged signals x(t) to the frequency domain (e.g., as a sinc function having a peak in frequency at beat frequency f_b). If desired, zero-padding circuitry on FFT **96** may zero-pad the averaged signals for interpolation in converting the averaged signals to the frequency domain. FFT **96** may provide the frequency domain averaged signals to frequency estimator **68** and phase estimator **72**.

Frequency estimator **68** may estimate beat frequency f_b based on the frequency domain averaged signals received from FFT **96**. For example, frequency estimator **68** may identify beat frequency f_b by identifying the frequency that corresponds to the peak value of the output of FFT **96**. Frequency estimator **68** may provide beat frequency f_b to phase ambiguity resolver **74** and phase estimator **72**. If desired, phase ambiguity resolver **74** may pass the beat frequency f_b estimated by frequency estimator **68** to range estimation circuitry **80**. Range estimation circuitry **80** may estimate a coarse range R_{fb} (e.g., a range R that is estimated based on beat frequency f_b only but not phase information) using equation 2.

$$R_{fb}=\frac{c*T1*f_b}{2B} \quad (2)$$

In equation 2, c is the speed of light. This is a very coarse range estimate dependent upon beat frequency f_b that does not consider beat phase ϕ_b. Combining phase information such as beat phase ϕ_b with the beat frequency may produce estimates of range R that are considerably more accurate than the coarse range R_{fb} estimated only using beat frequency f_b.

Phase estimator **72** may therefore estimate beat phase ϕ_b based on the frequency domain averaged signals received from FFT **96** to increase the accuracy of the range R estimated by range estimator **80**. Phase estimator **72** may, for example, estimate beat phase ϕ_b by measuring the phase corresponding to the peak value of the output of FFT **96**. Equation 3 describes the relation between range R and beat phase ϕ_b.

$$\phi_b=2\pi f_{min}*\frac{2R}{c}=\frac{4\pi R}{\lambda} \quad (3)$$

In equation 3, f_{min} is the starting FMCW ramp frequency (e.g., the lowest frequency in each of the K chirp signals corresponding to curve **52** of FIG. **3**) and X is the corresponding wavelength. As shown by equation 3, beat phase ϕ_b contains distance information (e.g., because beat phase ϕ_b is dependent upon the range R to be estimated). Direct estimation of range R using beat phase ϕ_b may therefore become challenging, due to phase wrapping that produces multiple solutions and thus phase ambiguity. For example, for f_{min}=60 GHz, there may be phase wrapping every

$$\frac{\lambda}{2}=2.5 \text{ mm}.$$

Phase ambiguity resolver **74** may resolve this phase ambiguity. For example, phase ambiguity resolver **74** may generate a phase ambiguity resolution value m according to equation 4.

$$m=\text{round}\left(\frac{R_{fb}-R_{initial}}{\frac{\lambda}{2}}-\frac{\phi_b-\phi_{initial}}{2\pi}\right) \quad (4)$$

In equation 4, round( ) is a rounding function that rounds its argument to the nearest integer, $R_{initial}$ is an earlier gathered range value R (e.g., for the immediately previous series of K beat signals sigb or for an earlier series of K beat signals sigb), and $\phi_{initial}$ is an earlier beat phase estimated by phase estimator **72** (e.g., for the immediately previous series of K beat signals sigb or for an earlier series of K beat signals sigb). Phase ambiguity resolver **74** may pass phase ambiguity resolution value m to range estimator **80**.

Range estimator **80** may estimate range R (e.g., an estimate that is more accurate than coarse range R_{fb}) based on the beat phase ϕ_b estimated by phase estimator **72** and phase ambiguity resolution value m. For example, range estimator **80** may estimate range R using equation 5.

$$R=R_{initial}+m*\frac{\lambda}{2}+\frac{(\phi_b-\phi_{initial})*\lambda}{4\pi} \quad (5)$$

The range R estimated by range estimator **80** according to equation 5 (e.g., based on both beat phase ϕ_b and coarse range R_{fb}, which is a factor in phase ambiguity resolution value m) is more accurate than the coarse range R_{fb} estimated based on beat frequency f_b alone. As an example, for f_{min}=60 GHz and B=5.28 GHz, the range R estimated using equation 5 may be 19 times more accurate than coarse range R_{fb} (e.g., where $\text{sqrt}(3f_{min}^2/B^2)=\text{sqrt}(3*60^2/5.28^2)=19$).

However, estimating range R using only beat frequency f_b and beat phase ϕ_b in this way (e.g., without considering beat phase velocity) can only be applied if coarse range R_{fb} is accurate enough to resolve the phase ambiguity. This may be possible only when the Cramer-Rao Lower Bound (CRLB) of R_{fb} is less than or equal to 1.25^2 mm^2, which corresponds to SNRs that are greater than or equal to about 25 dB. In other words, equations 1-5 may be used to estimate range R when the SNR of the averaged signals produced by vector integrator **92** are about 25 dB or greater.

However, in practice, sensing circuitry **28** may need to identify range R in a low SNR regime (e.g., where the SNR of the averaged signals produced by vector integrator **92** is less than 25 dB). For example, in scenarios where external object **45** is moving, the integration interval used by vector integrator **92** may be too short to produce a sufficiently high SNR. Under these conditions, the range estimation based on phase information is still very accurate, but the frequency estimation (e.g., beat frequency f_b) is not accurate enough to resolve the phase ambiguity. To resolve the phase ambiguity and therefore generate accurate estimates of range R in the low SNR regime despite beat frequency f_b being insufficiently accurate on its own to resolve the phase ambiguity, sensing receiver **48** may identify range R based on the beat phase velocity $\hat{\beta}$ of the received beat signals in addition to beat frequency f_b and beat phase ϕ_b. Beat phase velocity $\hat{\beta}$ may sometimes also be referred to herein simply as phase velocity $\hat{\beta}$.

As shown in FIG. **5**, sensing receiver **48** may include beat processing chains **94** and phase velocity estimator **88** for identifying beat phase velocity $\hat{\beta}$ based on the K beat signals output by ADC **90**. Each beat processing chain **94** may receive and/or operate on a respective one of the K beat signals output by ADC **90** (e.g., beat processing chain **94-1** may process the first of the beat signals, beat processing chain **94**-K may process the Kth of the beat signals, etc.). Each beat processing chain **94** may identify the beat phase ϕ_{bi} for its respective (e.g., ith) beat signal and thus for a respective one of the K chirps that produced the beat signal (e.g., beat processing chain **94-1** may identify beat phase ϕ_{b1} of the first beat signal and thus the first chirp, beat processing chain **94**-K may identify beat phase ϕ_{bK} of the Kth beat signal and thus the Kth chirp, etc.). The K beat processing chains **94** may generate the beat phases in parallel (e.g., concurrently).

The FFT **82** in each beat processing chain **94** may convert its beat signal to the frequency domain as a respective frequency domain signal chp (e.g., the FFT **82** in beat processing chain **94-1** may output frequency domain signal chpl, the FFT **82** in beat processing chain **94**-K may output frequency domain signal chpk, etc.). The beat signal input to FFT **82** (prior to conversion to the frequency domain) may be described mathematically by the right side of equation 1. If desired, zero-padding circuitry in each FFT **82** may perform zero-padding on its respective beat signal for interpolation in converting the beat signal to the frequency domain. Frequency domain signals chp may be, for example, sinc functions having a peak in frequency at the respective beat frequency f_{bi} of the corresponding beat signal.

The frequency estimator **84** in each beat processing chain **94** may identify (e.g., estimate, generate, calculate, compute, determine, deduce, output, etc.) the beat frequency f_{bi} of the beat signal received by that beat processing chain **94** (e.g., the frequency estimator **84** in beat processing chain **94-1** may identify the beat frequency f_{b1} of the first beat signal in the series of K beat signals, the frequency estimator **84** in beat processing chain **94**-K may identify the beat frequency f_{bK} of the Kth beat signal in the series of K beat signals, etc.). Frequency estimators **84** may identify beat frequencies f_{bi} by identifying the frequencies of the peaks of the outputs of FFTs **82** (e.g., the frequency of the peak of the curve shown in FIG. **6**). The frequency estimators **84** may pass beat frequencies f_{bi} to the phase estimator **86** in its beat processing chain **94**.

The phase estimator **86** in each beat processing chain **94** may identify (e.g., estimate, generate, calculate, compute, determine, deduce, output, etc.) the beat phase ϕ_{bi} of the beat signal received by that beat processing chain **94** (e.g., the phase estimator **86** in beat processing chain **94-1** may identify the beat phase ϕ_{b1} of the first beat signal in the series of K beat signals, the frequency estimator **86** in beat processing chain **94**-K may identify the beat phase ϕ_{bK} of the Kth beat signal in the series of K beat signals, etc.). Phase estimators **86** may identify beat phases ϕ_{bi} by identifying the phases of the peaks of the outputs of FFTs **82** (e.g., the phase of the peak of the curve shown in FIG. **6**). The phase estimators **86** may pass beat phases ϕ_{bi} to phase velocity estimator **88** in parallel (e.g., the phase estimator **86** in beat processing chain **94-1** may pass beat phase ϕ_{b1} to phase velocity estimator **88**, the phase estimator **86** in beat processing chain **94**-K may pass beat phase ϕ_{bK} to phase velocity estimator **88**, etc.). Operating on each of the K beat signals in parallel may optimize the timing efficiency of sensing receiver **48**, for example.

Phase velocity estimator **88** may identify the phase velocity $\hat{\beta}$ of the series of K beat signals based on the beat phases of each of the K beat signals (e.g., based on the K beat phases ϕ_{bi} received from beat processing chains **94**). The phase velocity may be a radial phase velocity, for example (e.g., phase velocity estimator **88** may be a radial phase velocity estimator). If desired, phase velocity estimator **88** may identify phase velocity $\hat{\beta}$ by performing a first-order polynomial fitting (e.g., a linear fit) over the K beat phases ϕ_{bi} received from beat processing chains **94** (e.g., where the phase velocity is defined by the slope of the linear fit). For example, phase velocity estimator **88** may generate (e.g., compute, calculate, generate, identify, produce, output, etc.) phase velocity $\hat{\beta}$, in units of radians per second, using equation 6.

$$\hat{\beta} = \frac{\Sigma_{i=1}^{K}\left(i - \frac{K+1}{2}\right)\left(\phi_{bi} - \overline{\phi}_b\right)}{T1 * \Sigma_{i=1}^{K}\left(i - \frac{K+1}{2}\right)^2} \tag{6}$$

In equation 6, $\overline{\phi}_b$ is the average of the K beat phases ϕ_{bi} and i is the integer index value from 1 to K. Phase velocity estimator **88** may pass phase velocity $\hat{\beta}$ to phase ambiguity resolver **74**.

Phase ambiguity resolver **74** and range estimator **80** may receive previous range information RPREV from range measurement database **70** over path **76**. Previous range information RPREV may include a previous range value $R_{previous}$ generated by sensing circuitry **48** for the previous series of K beat signals (e.g., for the immediately previous series of K beat signals sigb or for any earlier series of K beat signals sigb). Previous range information RPREV may also include a previous beat phase value $\phi_{previous}$. Previous beat phase value $\phi_{previous}$ may be the beat phase ϕ_b generated by phase estimator **72** for the previous series of K beat signals that were used to generate previous range value $R_{previous}$ (e.g., previous beat phase value $\phi_{previous}$ may be the beat phase ϕ_b used by sensing receiver **48** to generate previous range value $R_{previous}$). Phase ambiguity resolver **74** may resolve this phase ambiguity based on phase velocity $\hat{\beta}$ and the beat phase ϕ_b estimated by phase estimator **72** (e.g., for the current series of K beat signals) and based on previous range information RPREV (e.g., previous range value $R_{previous}$ and previous beat phase value $\phi_{previous}$). For example, phase ambiguity resolver **74** may generate (e.g.,

compute, calculate, identify, produce, output, etc.) a phase ambiguity resolution value n according to equation 7.

$$n = \text{round}\left(\frac{\hat{\beta}}{2\pi} * T2 - \frac{\phi_b - \phi_{previous}}{2\pi}\right) \quad (7)$$

Phase ambiguity resolver **74** may pass phase ambiguity resolution value n to range estimator **80**.

Range estimator **80** may identify (e.g., estimate, calculate, compute, determine, generate, output, produce, etc.) the current range R between device **10** and external object **45** based on phase ambiguity resolution value n, previous range information RPREV (e.g., previous range value $R_{previous}$ and previous beat phase value $\phi_{previous}$), and the beat phase ϕ_b for the current series of K beat signals. For example, range estimator **80** may identify range R using equation 8.

$$R = R_{previous} + n * \frac{\lambda}{2} + \frac{(\phi_b - \phi_{previous}) * \lambda}{4\pi} \quad (8)$$

Range estimator **80** may pass range R to other portions of control circuitry **14** for further processing. If desired, range estimator **80** may provide current range information RNEW to range measurement database **70**. Current range information RNEW may include beat phase ϕ_b (e.g., for use as previous beat phase value $\phi_{previous}$ during processing of a subsequent series of K beat signals) and range R (e.g., for use as previous range value $R_{previous}$ during processing of the subsequent series of K beat signals). Range measurement database **70** may store current range information RNEW (e.g., for use as previous range information RPREV during processing of a subsequent series of K beat signals).

FIG. **6** is a frequency space plot of a frequency domain signal chp that may be produced by the FFT **82** in a given one of beat signal processing chains **94**. As shown in FIG. **6**, frequency domain signal chp may be a sinc function having a peak at the corresponding beat frequency f_{bi}. Frequency estimator **84** may identify the beat frequency f_{bi} of frequency domain signal chp. Phase estimator **86** may identify the phase of frequency domain signal chp (e.g., at beat frequency f_{bi}) as the beat phase ϕ_{bi} of frequency domain signal chp (e.g., the beat phase of the corresponding beat signal). The example of FIG. **6** is merely illustrative and the curve shown in FIG. **6** may have other shapes in practice.

FIG. **7** is a plot showing how phase velocity estimator **88** may identify phase velocity $\hat{\beta}$ based on the K beat phases ϕ_{bi} received from beat processing chains **94**. In the example of FIG. **7**, K=16, sample number (index i) is plotted on the horizontal axis, and phase is plotted on the vertical axis (e.g., in radians). The horizontal axis may also represent time, because each sample is separated by chirp duration T**1**. Each of the K=16 beat phases ϕ_{bi} (e.g., a first beat phase a second beat phase ϕ_{b2}, a 16^{th} beat phase ϕ_{b16}, etc.) are plotted as points in FIG. **7**. Phase velocity estimator **88** may fit the 16 beat phases ϕ_{bi} with first order polynomial (line) **98**. Phase velocity $\hat{\beta}$ is represented by the slope of line **98**. Phase velocity estimator **88** may therefore identify phase velocity $\hat{\beta}$ by identifying (e.g., generating, computing, calculating, producing, outputting, estimating, etc.) the slope of line **98** (e.g., according to equation 6). The example of FIG. **7** is merely illustrative. In practice, beat phases ϕ_{bi} may have other values. K may be any desired integer (e.g., less than 16, at least 2, at least 4, at least 8, greater than 16, at least 32, at least 64, at least 128, etc.).

FIG. **8** is a flow chart of illustrative operations that may be performed by sensing circuitry **48** to generate range R from a series of K beat signals sigb. The operations of FIG. **8** may, for example, be performed while processing operation **66** of FIG. **4**.

At operation **100**, ADC **90** may receive a series (sequence) of K consecutive beat signals sigb. ADC **90** may convert the series of K beat signals to the digital domain and may pass the digital domain beat signals to vector integrator **92** and beat processing chains **94**.

At operation **102**, vector integrator **92** may average the series of K beat signals (in the digital domain) to generate averaged signals x(t).

At operation **104**, FFT **96** may convert averaged signals x(t) to the frequency domain.

At operation **106**, frequency estimator **68** may estimate (e.g., identify, determine, generate, produce, output, calculate, compute, etc.) beat frequency f_b based on the averaged signals (in the frequency domain). Frequency estimator **68** may pass beat frequency f_b to phase estimator **72** and phase ambiguity resolver **74**. Phase estimator **72** may estimate (e.g., identify, determine, generate, produce, output, calculate, compute, etc.) beat phase ϕ_b based on the averaged signals (in the frequency domain). Phase estimator **72** may pass beat phase ϕ_b to phase ambiguity resolver **74** and range estimator **80**.

At operation **108**, each of the K beat phase processing chains **94** in sensing receiver **48** may generate a respective beat phase ϕ_{bi} based on a respective one of the K beat signals output by ADC **90** (e.g., in parallel). For example, the FFT **82** in each beat processing chain **94** may convert its beat signal to the frequency domain (e.g., as frequency domain signals chp). The frequency estimator **84** in each beat processing chain **94** may generate beat frequency f_b; based on frequency domain signals chp. The phase estimator **86** in each beat processing chain **94** may generate beat phase ϕ_{bi} based on frequency domain signals chp. Each beat processing chain **94** may pass its beat phase ϕ_{bi} to phase velocity estimator **88**.

At operation **110**, phase velocity estimator **88** may generate phase velocity $\hat{\beta}$ based on the K beat phases ϕ_{bi} received from beat processing chains **94**. Phase velocity estimator **88** may generate phase velocity $\hat{\beta}$ using a linear fit of the K beat phases ϕ_{bi} over time (sample number) (e.g., according to equation 6). Phase velocity estimator **88** may pass phase velocity $\hat{\beta}$ to phase ambiguity resolver **74**.

At operation **112**, range measurement database **70** may provide previous range information RPREV to phase ambiguity resolver **74** and range estimator **80**. Previous range information RPREV may include a previous range value $R_{previous}$ and a previous beat phase value $\phi_{previous}$ gathered from an earlier series of K beat signals (e.g., during an immediately previous iteration of the operations of FIG. **8** or during some earlier iteration).

At operation **114**, phase ambiguity resolver **74** may resolve the phase ambiguity by generating phase ambiguity resolution value n based on phase velocity $\hat{\beta}$, beat phase ϕ_b, and previous range information RPREV (e.g., according to equation 7). Phase ambiguity resolver **74** may pass phase ambiguity resolution value n to range estimator **80**.

At operation **116**, range estimator **80** may generate current (updated) range information RNEW based on previous range information RPREV, phase ambiguity resolution value n, and beat phase ϕ_b (e.g., according to equation 8). Current range information RNEW may include a current (updated) range value R and the current beat phase ϕ_b, for example. Range estimator **80** may provide current range information

RNEW to other portions of control circuitry **14** (FIG. **1**) and/or to range measurement database **70** for storage. Processing may loop back to operation **100** via path **118** as a subsequent series of K beat signals is received at ADC **90**. Current range information RNEW may form previous range information RPREV for the subsequent series of K beat signals (e.g., for the subsequent iteration of operations **100-116**) and/or for later series of K beat signals, for example. The example of FIG. **8** is merely illustrative. Operations **102**, **104**, and/or **106** may be performed concurrently with operations **108**, **110**, and/or **112**.

Generating current range information RNEW in this way may allow sensing receiver **48** to accurately measure range R to external device **45** in the low SNR regime (e.g., at SNRs below about 25 dB), such as in scenarios where external device **45** is in motion. If desired, measuring phase velocity for generating current range information RNEW may be omitted when SNR is in the high SNR domain (e.g., at SNRs above about 25 dB). In other words, sensing receiver **48** may measure range R based on beat frequency f_b and/or beat phase ϕ_b in the high SNR regime (e.g., because beat frequency f_b may be sufficient to resolve the phase ambiguity in beat phase ϕ_b in the high SNR domain) and may measure range R based on beat phase ϕ_b and/or the beat velocity in the low SNR regime.

FIG. **9** is a plot of phase ambiguity identification rate as a function of SNR showing how the measuring phase velocity may allow for accurate range measurements in the low SNR domain. Curve **118** plots the phase ambiguity identification (resolution) rate of sensing receiver **48** when estimating range R based only on beat frequency f_b and beat phase ϕ_b. As shown by curve **118**, sensing receiver **48** may be able to resolve (identify) all or nearly all of the phase ambiguities in beat phase ϕ_b when in high SNR regime **124**. However, the amount of phase ambiguities resolvable by sensing receiver **48** deteriorates as SNR decreases within low SNR regime **122**.

Curve **120** plots the phase ambiguity identification (resolution) rate of sensing receiver **48** when identifying range R based on beat phase ϕ_b and phase velocity $\hat{\beta}$. As shown by curve **120**, identifying range R using phase velocity $\hat{\beta}$ allows sensing circuitry **48** to resolve all or nearly all of the phase ambiguities in beat phase ϕ_b, thereby producing accurate ranges R, in both high SNR regime **124** and low SNR regime **122**. In other words, generating ranges R based at least on beat phase velocity $\hat{\beta}$ may minimize the presence of errors in ranges R even when SNR is relatively low (e.g., at or below 0 dB). Allowing for accurate measurement of ranges R at low SNR may allow device **10** to accurately track the location of external object **45** even if external object **45** is moving. This may allow sensing circuitry **48** to identify gesture inputs, stylus inputs, and/or perform any other desired processing tasks based on the position, orientation, range, and/or velocity of external object **45** even when external object **45** is moving relatively quickly relative to device **10**. The example of FIG. **9** is merely illustrative. Curves **120** and **118** may have other shapes in practice.

Device **10** may gather and/or use personally identifiable information. It is well understood that the use of personally identifiable information should follow privacy policies and practices that are generally recognized as meeting or exceeding industry or governmental requirements for maintaining the privacy of users. In particular, personally identifiable information data should be managed and handled so as to minimize risks of unintentional or unauthorized access or use, and the nature of authorized use should be clearly indicated to users.

The methods and operations described above in connection with FIGS. **1-9** (e.g., the operations of FIGS. **4** and **8**) may be performed by the components of device **10** using software, firmware, and/or hardware (e.g., dedicated circuitry or hardware). Software code for performing these operations may be stored on non-transitory computer readable storage media (e.g., tangible computer readable storage media) stored on one or more of the components of device **10** (e.g., storage circuitry **16** of FIG. **1**). The software code may sometimes be referred to as software, data, instructions, program instructions, or code. The non-transitory computer readable storage media may include drives, non-volatile memory such as non-volatile random-access memory (NVRAM), removable flash drives or other removable media, other types of random-access memory, etc. Software stored on the non-transitory computer readable storage media may be executed by processing circuitry on one or more of the components of device **10** (e.g., processing circuitry **18** of FIG. **1**, etc.). The processing circuitry may include microprocessors, central processing units (CPUs), application-specific integrated circuits with processing circuitry, or other processing circuitry. While databases are sometimes described herein as providing data to other components (see, e.g., range measurement database **70** of FIG. **5**), one or more processors, memory controllers, or other components may actively access the databases, may retrieve the stored data from the database, and may pass the retrieved data to the other components for corresponding processing.

The foregoing is merely illustrative and various modifications can be made to the described embodiments. The foregoing embodiments may be implemented individually or in any combination.

What is claimed is:

1. An electronic device comprising:

one or more antennas configured to transmit radio-frequency sensing signals and configured to receive reflected radio-frequency sensing signals;

a mixer configured to generate beat signals based on the radio-frequency sensing signals and the reflected radio-frequency sensing signals; and

one or more processors configured to

estimate a range between the electronic device and an external object based on a beat phase of the beat signals and a beat phase velocity of the beat signals, and

resolve a phase ambiguity in the beat phase based on the beat phase velocity.

2. The electronic device of claim **1**, wherein the radio-frequency sensing signals comprise a series of chirp signals, the reflected radio-frequency sensing signals comprise a series of reflected chirp signals, and the beat signals comprise a series of beat signals, each beat signal in the series of beat signals being generated based on a respective one of the chirp signals in the series of chirp signals and a respective one of the reflected chirp signals in the series of reflected chirp signals.

3. The electronic device of claim **2**, the one or more processors being configured to generate a set of beat phase values in parallel and wherein the one or more processors is configured to generate each beat phase value in the set of beat phase values based on a respective beat signal in the series of beat signals.

4. The electronic device of claim **3**, the one or more processors being configured to generate the beat phase velocity based on the set of beat phase values.

5. The electronic device of claim 4, the one or more processors being configured to generate the beat phase velocity by performing a linear fit over the set of beat phase values.

6. The electronic device of claim 4, the one or more processors being configured to:

average the series of beat signals to generate an averaged signal;

convert the averaged signal to a frequency domain; and

generate the beat phase based on the averaged signal in the frequency domain.

7. The electronic device of claim 6, the one or more processors being configured to estimate the range based on the beat phase and the beat phase velocity when a signal-to-noise ratio of the averaged signal is less than a threshold level.

8. The electronic device of claim 7, the one or more processors being configured to estimate the range based on the beat phase but not the beat phase velocity when the signal-to-noise ratio of the averaged signal exceeds the threshold level.

9. The electronic device of claim 1, the one or more processors being configured to:

generate a phase ambiguity resolution value by applying a rounding function to an argument that includes the beat phase velocity, the beat phase, and an additional beat phase; and

estimate the range based on the phase ambiguity resolution value, the beat phase, and a previous range between the electronic device and the external object estimated by the one or more processors, the previous range being estimated by the one or more processors based on the additional beat phase.

10. The electronic device of claim 1, wherein the sensing signals comprise a linear frequency ramp having a duration and the beat phase velocity is inversely proportional to the duration of the linear frequency ramp.

11. A method of operating an electronic device having antennas, a mixer, and one or more processors, the method comprising:

with the mixer, generating a series of beat signals from radio-frequency sensing signals transmitted by one or more of the antennas and a reflected version of the radio-frequency sensing signals received by one or more of the antennas;

with the one or more processors, generating a beat phase from an average of the series of beat signals;

with the one or more processors, generating a phase velocity of the series of beat signals; and

with the one or more processors, generating a range value associated with a distance between the electronic device and an external object based on the beat phase and the phase velocity.

12. The method of claim 11, wherein generating the phase velocity comprises:

generating a respective phase value of each beat signal in the series of beat signals in parallel; and

generating the phase velocity based on the phase values.

13. The method of claim 12, wherein generating the phase velocity based on the phase values comprises performing a linear fit of the phase values.

14. The method of claim 12, further comprising:

generating a phase ambiguity resolution value based on the phase velocity, the beat phase, and a previous beat phase associated with a previous series of beat signals generated by the mixer.

15. The method of claim 14, wherein generating the range value comprises:

generating the range value based on the phase ambiguity resolution value, the beat phase, the previous beat phase, and a previous range value generated by the one or more processors.

16. The method of claim 15, further comprising identifying an input gesture based at least on the range value and the previous range value.

17. The method of claim 15, further comprising:

with the one or more processors, generating the average of the series of beat signals by performing vector integration on the series of beat signals;

with the one or more processors, converting the average of the series of beat signals to a frequency domain average of the series of beat signals; and

with the one or more processors, generating the beat phase based on the frequency domain average of the series of beat signals.

18. A non-transitory computer-readable storage medium storing one or more programs configured to be executed by at least one processor on an electronic device, the one or more programs including instructions that, when executed by the at least one processor, cause the at least one processor to:

generate an average value of a series of beat signals associated with radio-frequency sensing signals transmitted and received by the electronic device;

generate a beat phase based on the average value;

generate a set of phase values, wherein each phase value in the set of phase values is generated based on a respective beat signal in the series of beat signals;

generate a beat phase velocity based on the set of phase values; and

estimate a range between the electronic device and an external object based on the beat phase and the beat phase velocity.

19. The non-transitory computer-readable storage medium of claim 18, the one or more programs including instructions that, when executed by the at least one processor, cause the at least one processor to:

resolve a phase ambiguity of the beat phase based on the beat phase velocity.

20. The non-transitory computer-readable storage medium of claim 19, the one or more programs including instructions that, when executed by the at least one processor, cause the at least one processor to:

generate a phase ambiguity resolution value based on the beat phase velocity, the beat phase, and a previous beat phase associated with a previous series of beat signals processed by the at least one processor; and

estimate the range based on the phase ambiguity resolution value, the beat phase, the previous beat phase, and a previous range between the electronic device and the external object estimated by the at least one processor.

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